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# Network Planning for Dual Residential-Business Exploitation of Next-Generation Passive Optical Networks to Provide Symmetrical 1 Gb/s Services

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Abstract—Demand for high-speed access for business and residential subscribers has grown rapidly in recent years; thus, service providers need to offer cost-effective solutions to cover this demand. Convergence within the same infrastructure for clients requiring different service levels may have benefits in terms of cost, but their respec-tive service-level specifications need to be guaranteed. This article compares different flavors of next-generation passive optical networks (PONs), namely, gigabit PON (GPON), 10-gigabit PON (XG-PON), time and wavelength division multiplexing PON (TWDM-PON), and wavelength division multiplexing PON (WDM-PON), and evaluates which one can provide 1 Gb/s symmetrical service at the more affordable cost when there is a mix of residential and business subscribers. Results show that the recom-mended technology depends on the percentage of business subscribers in the scenario.

Communication systems and economics; Network deployment optimization; Next-generation optical access; Optical network design; Passive optical network; TWDM-PON; WDM-PON.

## I. Introduction

At present, some network operators have begun to of-fer 1 Gb/s downstream Internet access to both residential and business customers. Symmetrical gigabit capacity may not be strictly required in residential scenarios, but customers appreciate such bandwidth as a means to enhance user experience, especially given the ever-increasing number of devices connected at home (laptops, tablets, smartphones, smart TVs, video-gaming devices, etc.) running applications that generate upstream traffic. Premium subscribers, however (for example, backhaul or business use cases), may require symmetrical gigabit capacity from day one. In any case, fiber optics is the technology of choice in the medium and long term due to its speed, reach, and, especially, its capability to deliver symmetric-rate services.

Given the observed fact that only a few subscribers are simultaneously active in residential scenarios [1], oversubscription-based capacity planning has been traditionally used by network operators, thus leveraging statistical multiplexing gains to reduce the cost of deployment. The question is to what extent residential and business users can be mixed on the same passive optical network (PON) while keeping their respective service level agreements.

This article aims at evaluating standard and emerging next-generation PON technologies [2], both in terms of deployment cost and ability to provide symmetrical 1 Gb/s capacity with oversubscription, and shows its applicability in a greenfield scenario. Selected split ratios for the different technologies are shown as the only feasible solution to satisfy the minimum service level agreements required. Furthermore, we implement a mixed integer linear programming (MILP) model extending [3] to optimize the cost of fiber deployments, after selecting those technologies and configurations that can actually provide 1 Gb/s symmetrical services to both residential and business users, each having a different set of requirements. Results show that, although time and wavelength division multiplexing PON (TWDM-PON) is the most economical solution when the number of business subscribers is not dominant, wavelength division multiplexing PON (WDM-PON) is the most convenient alternative for high business subscriber ratios on the PON.

The rest of this paper is organized as follows: Section II provides a taxonomy of fiber-to-the-home (FTTH) access protocols that support 1 Gb/s symmetrical services for residential and business customers. Section III reviews basic methodology used in capacity planning with oversubscription, as often used by network operators. Section IV develops the optimization framework and model that selects the lowest-cost geographical network deployment. Section V applies the optimization model and develops a cost-minimized comparison, amongst the different technologies for residential and business services. Finally, Section VI concludes this article with a summary of its main results along with future work worth investigation.

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## II. Taxonomy of Fiber Access Protocols to Provide 1 Gbit/s Symmetrical Services

The physical fiber topology that connects the operator premises and the subscriber premises, also called an optical distribution network (ODN), can be point-to-point, point-to-multipoint (often referred to as PON or ring). Point-to-point and PON are, so far, the topologies most commonly deployed in real implementations. This paper focuses on protocols for PON topologies, namely, TDM-PON; WDM-PON; and the hybrid version, time, and wavelength, called TWDM-PON.

As shown in Table I, TDM-PON technology (gigabit PON, GPON [4]; 10-gigabit PON, XG-PON [5]) uses a shared point-to-multipoint approach with one or two wavelengths in the downstream direction, and one wavelength in the upstream (from users to central office). GPON offers 2.5G/1.25G, while XG-PON offers 10G/2.5G in the down and upstream directions, respectively. TWDM-PON [6] takes one step forward with respect to XG-PON, increasing

TABLE I
Summary of Features for PON Technologies

| | GPON | XG-PON | TWDM-PON | WDM-PON |
|---|---|---|---|---|
| Standard | ITU-T G.984 | ITU-T G.987 | ITU-T G.989 | ITU-T G.698.3 |
| Availability | In market | In market | In-progress | In market |
| Feeder rate ($C_{DL}/C_{UL}$) | 2.5G/1.25G | 10G/2.5G | 40G/10G | 32G/32G |
| Security | No | No | No | Yes |
| Outside Plant | Splitter | Splitter | Splitter with WDM mux | AWG |
| Price | Lower | Medium | Medium | Higher |
| Power budget (dB) | 28 (B+) | 35 (E2) | 38.5 | 15 |

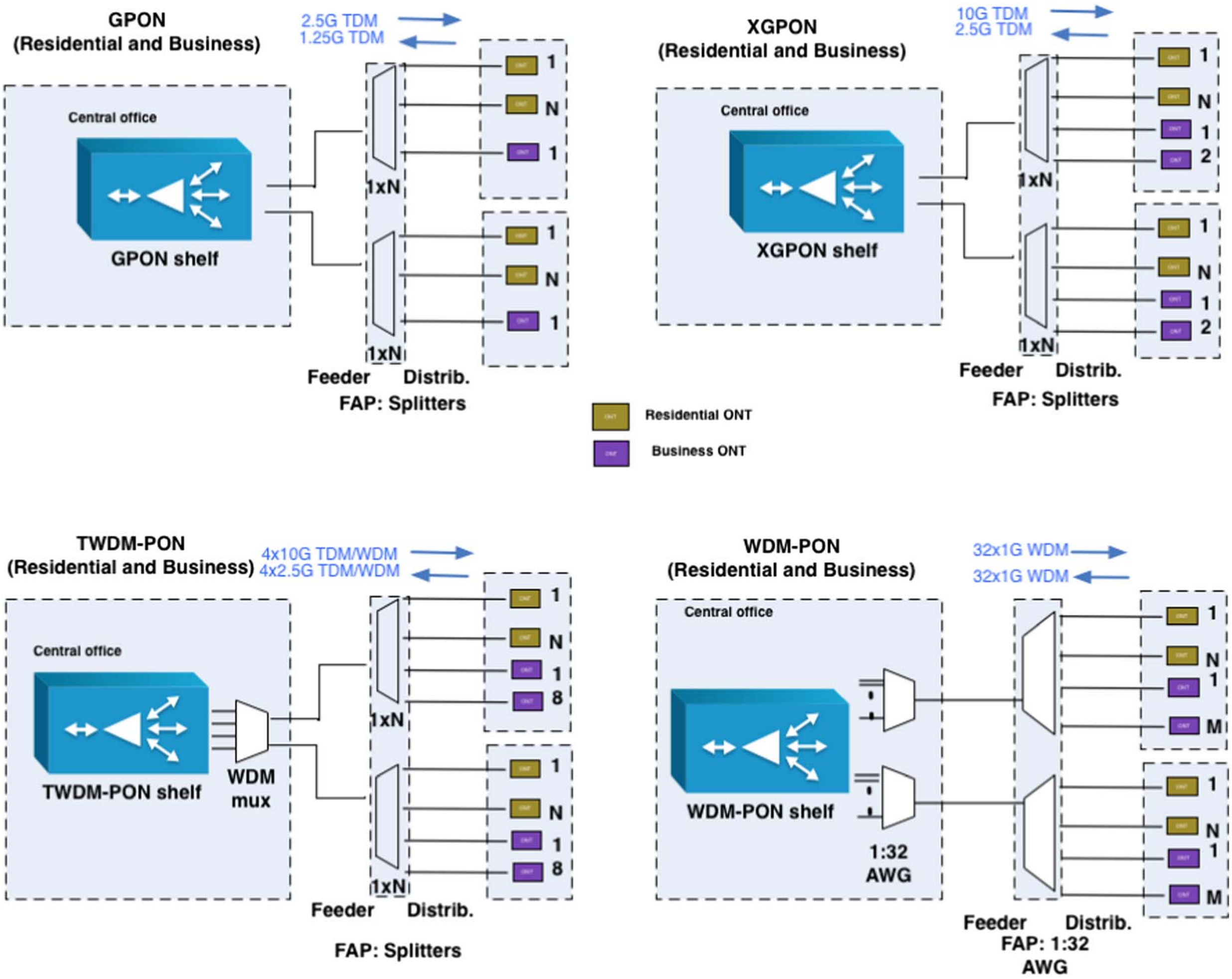


Fig. 1. Taxonomy of PON fiber-access protocols.

the aggregate PON rate by stacking multiple XG-PONs on different pairs of wavelengths, which yields an aggregate $N \times 10$ Gb/s downstream and $N \times 2.5$ Gb/s upstream [7]. Finally, with AWG-based WDM-PON [8], dedicated wavelengths are directed to the ONTs from the central office via a passive wavelength router (AWG) located in the outside plant. Relevant research works [9–11] explain additional details about all those technologies.

Figure 1 shows the topologies under consideration in this paper. They are single-level tree topologies in order to keep the MILP model as simple as possible, although it is more common to find two-level tree topologies in real deployments. Enhancing the model to two-level trees is straightforward, and it would simply imply the duplication of variables and the connectivity constraints. This would not add any substantial value to the work and the conclusions about cost comparison are not expected to change significantly if all topologies are of the same type (either one or two-level) in all technologies.

For reasons explained in the next sections, related to oversubscription-based capacity planning, not all split ratios are suitable to comply with service levels of residential and business subscribers:

1) *GPON:* This topology considers GPON between 1:1 and 1:16 split ratios for residential and business subscribers. The split ratio is limited to such values as explained later in the paper.
2) *XG-PON:* This topology considers XG-PON between 1:2 and 1:16 split for residential and business subscribers. 1:1 split is not considered in order to not under-utilize the 2.5G uplink (limiting factor).
3) *TWDM-PON:* This topology considers TWDM-PON with $4 \times 10$ Gb/s downstream and $4 \times 2.5$ Gb/s upstream aggregated capacity. Split ratios range between 1:8 and 1:64 split for residential and business subscribers. Lower split ratios are not used in order to not under-utilize the upstream capacity.
4) *WDM-PON:* This topology considers WDM-PON for residential and business subscribers, with 1:32 AWG.

The next sections study the suitability of GPON, XG-PON, AWG-based WDM-PON, and TWDM-PON to provide 1 Gb/s symmetrical services to residential and business customers and develops an optimization framework to calculate the optimal cost for each scenario in a given geographical area.

## III. Capacity Planning and Oversubscription

### A. Overview of Oversubscription Calculus

Oversubscription-based capacity planning in access networks works well because of the empirical observation that only a small portion of subscribers are simultaneously active at a given random instant [12]. Network designers leverage this fact to provide access to a large number of users at a moderate expense of resources. In all the analysis, we assume best-effort Internet service to dominate the PON.

Let $r_{\text{tot}}$ refer to the maximum *number of users physically attached* to the same PON branch; here, $r_{\text{tot}}$ can take only a small set of discrete values, namely, $r_{\text{tot}} \in \{1, 2, 4, 8, 16, 32, 64\}$. This range of $r_{\text{tot}}$ only applies to GPON, XG-PON, and TWDM-PON technologies because, for WDM-PON deployments, we consider $r_{\text{tot}} = 32$ fixed (see Fig. 1).

Next, let $r_{\text{act}}$ refer to the random variable that considers the number of *active users* at a given random time. Clearly, $0 \le r_{\text{act}} \le r_{\text{tot}}$. For simplicity, we consider users' activity as independent and identically distributed Bernoulli random variables, i.e., they are active with probability $q$ or idle with probability $1 - q$.

Under these assumptions, $r_{\text{act}}$ follows a binomial distribution characterized by two parameters, i.e., $r_{\text{act}} \sim B(r_{\text{tot}}, q)$. Its probability density function (PDF) is

$$P(r_{\text{act}} = k) = \binom{r_{\text{tot}}}{k} q^k (1-q)^{r_{\text{tot}}-k}, \qquad k = 0, 1, \ldots, r_{\text{tot}}. \quad (1)$$

Many measurement studies have reported that the empirically observed value of $q$ is very small [13,14].

Concerning capacity in terms of transmission rate made available to the user (we shall use the colloquial term *bandwidth*), let us define $b_{\text{peak}}$ as the maximum rate allowed per user (in the following $b_{\text{peak}} = 1$ Gb/s), and let $b$ denote the random variable that characterizes the rate observed per individual user in the PON branch. Clearly, the bandwidth $b$ observed by the users depends on how many users are active at a particular time from the total; in other words,

$$b(r_{\text{act}}) = \min\left\{\frac{C_{UL}}{r_{\text{act}}}, b_{\text{peak}}\right\}, \quad (2)$$

where $b$ may never exceed the value of $b_{\text{peak}}$. Here, $C_{UL}$ is the upstream capacity of each NG-PON technology (see Table I). It is worth noting that the upstream bandwidth is the limiting resource to provide 1 Gb/s symmetrical service because the downlink bandwidth $C_{DL}$ is typically greater than this.

Equation (2) states that the total upstream bandwidth $C_{UL}$ Gb/s is equally shared among the number of active users in the PON. Furthermore, $b$ is a discrete random variable that depends on the number of active users: the smaller the value of $r_{\text{act}}$, the larger bandwidth rate experienced per user, limited by $b_{\text{peak}}$. On the contrary, when all users are active ($r_{\text{act}} = r_{\text{tot}}$), all users are guaranteed at least a minimum rate of $\frac{C_{UL}}{r_{\text{tot}}}$.

The random variables $b$ and $r_{\text{act}}$ are related as follows:

$$P\left(b \ge \frac{C_{UL}}{k}\right) = P(r_{\text{act}} \le k), \quad \text{with } r_{\text{act}} \sim B(r_{\text{tot}}, q), \quad (3)$$

meaning that users receive more than $C_{UL}/k$ bandwidth only when the number of active users is below $k$.

In general, it is unlikely to have many active users when $q$ is sufficiently small. In the literature, network designers often use the term *oversubscription ratio o* to refer to the maximum carried traffic divided by the worst-case maximum bandwidth capacity *demanded* by all users; in other words,

$$o = \frac{C_{UL}}{r_{\text{tot}} b_{\text{peak}}}. \tag{4}$$

The following two metrics are of particular interest in the design of an access network under the oversubscription model:

- the average bandwidth observed per user for a given total number of users $r_{\text{tot}}$ and activity $q$,
- the percentage of time (in what follows, $\beta$) whereby $b_{\text{peak}} = 1$ Gb/s is granted to a given user.

The average bandwidth perceived by the users must take into account the number of active users along with their probabilities, namely,

$$E(b) = \sum_{k=0}^{r_{\text{tot}}} b(k) P(r_{\text{act}} = k). \tag{5}$$

Concerning the value of $\beta$, i.e., the probability that a given user is provided $b_{\text{peak}}$, it is worth noting that $b_{\text{peak}}$ is guaranteed when no more than $r_{\text{act}}^{(\max)}$ users are active, namely,

$$r_{\text{act}}^{(\max)} = \left\lfloor \frac{C_{UL}}{b_{\text{peak}}} \right\rfloor. \tag{6}$$

Thus, $\beta$ equals to the probability that no more than $r_{\text{act}}^{(\max)}$ users are simultaneously active, in other words,

$$\begin{aligned} \beta &= P(r_{\text{act}} \le r_{\text{act}}^{(\max)}) \\ &= \sum_{k=0}^{\left\lfloor \frac{C_{UL}}{b_{\text{peak}}} \right\rfloor} \binom{r_{\text{tot}}}{k} q^k (1-q)^{r_{\text{tot}}-k}. \end{aligned} \tag{7}$$

Finally, Eqs. (5) and (7) provide a means to compute the average bandwidth and percentage of time whereby $b_{\text{peak}}$ is provided to users as a function of $r_{\text{tot}}$ and $q$. However, in network planning, we start from a requirement of $\beta$, an observed value of $q$ and the goal is to find the maximum number of users allowed per PON branch $r_{\text{tot}}$ such that $b_{\text{peak}}$ is provided during at least $\beta$ percent of the time. In other words, this comprises

$$\text{Find } r_{\text{tot}} \text{ such that } P(r_{\text{act}} \le r_{\text{act}}^{(\max)}) \ge \beta. \tag{8}$$

The next section shows the numbers of $E(b)$ and $\beta$ for a given set of parameters $r_{\text{tot}}$ and $q$.

### *B. Split Ratio: Numerical Example for Residential Subscribers*

Consider a GPON ($C_{UL}^{(\text{GPON})} = 1.25$ Gb/s) with $q = 0.15$ (i.e., 15% activity per user) and $r_{\text{tot}} = 32$ users. First, the maximum number of active users in order to guarantee $b_{\text{peak}} = 1$ Gb/s during 100% of the time is clearly $r_{\text{act}}^{(\max)} = 1$ user because two active users would have to share 1.25 Gb/s. Following the binomial distribution, the average number of active users in this particular case is

$$E(r_{\text{act}}) = r_{\text{tot}} q = 4.8 \text{ users},$$

and the average bandwidth is

$$\begin{aligned} E(b) &= \sum_{k=0}^{1} b_{\text{peak}} \binom{32}{k} q^k (1-q)^{32-k} \\ &\quad + \sum_{k=2}^{32} \frac{C_{UL}^{(\text{GPON})}}{k} \binom{32}{k} q^k (1-q)^{32-k} \\ &= 323 \text{ Mb/s}, \end{aligned}$$

as it follows from Eq. (5).

In the unlikely event that all users are active, i.e., $r_{\text{act}} = r_{\text{tot}}$, which occurs with probability

$$P(r_{\text{act}} = 32) = q^{32} = 4.3 \times 10^{-27},$$

the bandwidth experienced per active user is only $E(b) = 39$ Mb/s. This is the minimum absolute guaranteed bandwidth during 100% of the time.

Because most users are idle most of the time, the next stage is to see the probability that only $r_{\text{act}}^{(\max)} = 1$ user is active in the PON branch, thus receiving $b_{\text{peak}}$ bandwidth. Following the binomial distribution, the probability of having 1 active user or less in the PON is only 3.7%.

Now, consider that the operator's requirement is that all users must receive $b_{\text{peak}} = 1$ Gb/s during at least $\beta = 20\%$ of the time. In this case, having $r_{\text{tot}} = 32$ does not meet this requirement because the probability of having one active user is only 3.7%. Thus, a smaller number of users in the PON is needed; in particular, the value of $r_{\text{tot}}$ can be no larger than 18 total users because $P(r_{\text{act}} \le 1) = 0.22$ when $r_{\text{act}} \sim B(r_{\text{tot}} = 18, q = 0.15)$, but $P(r_{\text{act}} \le 1) = 0.198$ when $r_{\text{act}} \sim B(r_{\text{tot}} = 19, q = 0.15)$. Because $r_{\text{tot}}$ can only take discrete values in $\{1, 2, 4, 8, 16, 32, 64\}$, the maximum split ratio must be at most 1:16 ($r_{\text{tot}} = 16$ total users per PON branch). In this case, the average bandwidth experienced by users is now $E(b) = 612$ Mb/s [Eq. (5)] and $b_{\text{peak}} = 1$ Gb/s is provided during exactly 28.4%.

In the case of XG-PON, when $C_{UL}^{(\text{XG-PON})} = 2.5$ Gb/s, $b_{\text{peak}} = 1$ Gb/s is guaranteed when there are no more than $r_{\text{act}}^{(\max)} = 2$ active users in the PON branch. For the same $\beta = 20\%$ criteria as before and $q = 15\%$, the maximum number of users in the PON branch rises to $r_{\text{tot}} \le 27$. Again, the maximum split is 1:16 (16 users at most), which yields an average bandwidth rate $E(b) = 940$ Mb/s. Two

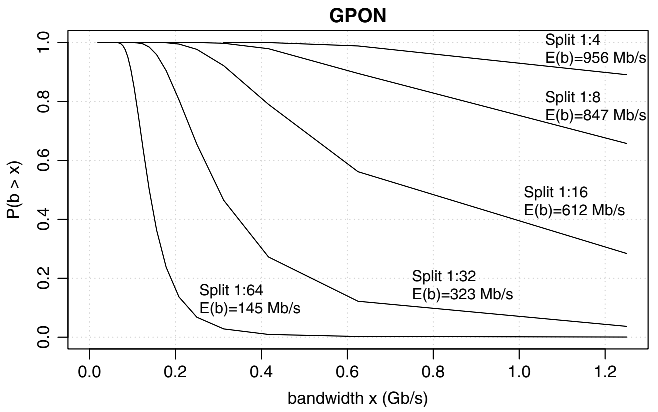


Fig. 2. GPON–CCDF of $b$ and average bandwidth for different split ratios, $q = 15\%$.

active users or less in the PON occurs during exactly 56.1% of the time in this example.

Figure 2 shows the complementary cumulative distribution function (CCDF) of $b$ for GPON with different split ratios [see Eq. (3)] along with the average bandwidth rate $E(b)$. As shown, the cases 1:64 and 1:32 show very small percentages where 1 Gb/s is provided (3.67% and 0.04%, respectively) and small values of average bandwidth $E(b)$.

Furthermore, Table II shows the average rate $E(b)$ observed and the percentages of time $\beta$ where $b_{\text{peak}}$ is guaranteed for all NG-PON technologies and different split ratios. The values of TWDM-PON have been computed taking into account that a stacking of four XG-PON technologies is shared among $r_{\text{tot}}$ users. In other words, we have computed the $E(b)$ and $\beta$ values for an XG-PON with $\frac{r_{\text{tot}}}{4}$ users.

When $q = 15\%$, XG-PON significantly improves the results of GPON providing 1 Gb/s rate during at least 50% for the split ratios 1:8 and 1:16. TWDM-PON provides 1 Gb/s during most of the time for split ratios 1:32 and below. When large user activity periods are expected, for instance, $q = 50\%$, only TWDM-PON with 1:8 and 1:16 split ratios ($r_{\text{tot}}$) can provide 1 Gb/s bandwidth during a substantial percentage of time.

Finally, it is worth remarking that WDM-PON provides a dedicated point-to-point connection between each user and the optical line terminal (OLT) with 1 Gb/s guaranteed 100% of the time for $r_{\text{tot}} = 32$ users regardless of the user activity $q$.

### C. Business and Residential Users in the Same PON

The previous analysis has considered that all users show the same activity $q$ and have the same $\beta$ requirement. However, this article is about providing an algorithm for dimensioning PON networks with two different types of users, namely, (1) residential users that show low values of $q$ and demand 1 Gb/s only for a low value of $\beta$, and (2) business users that show large values of $q$ and require 1 Gb/s during 100% of the time.

In particular, we shall consider $q_b = 0.5$ for business and a strict requirement of 1 Gb/s available during $\beta_b = 100\%$ of the time, whereas residential users show $q_r = 0.15$ and only require 1 Gb/s during $\beta_r = 20\%$ of the time. This service differentiation in terms of $\beta$ rather than in terms of bandwidth requires a specific configuration of the dynamic bandwidth allocation algorithm running at the OLT. It is worth remarking that the ITU-T standards allow to define fixed, assured, non-assured, and best-effort bandwidth; therefore, business users would be guaranteed $b_{\text{peak}}$ whenever they needed (only 50% of the time) thanks to the assured bandwidth service, whereas the residential users would be provided non-assured guarantees.

Now, concerning GPON, there can be 0 or 1 business users ($r_b$ in what follows) at most, because two business users would not be guaranteed 1 Gb/s each during 100% of the time. On the other hand, in the case of XG-PON (2.5 Gb/s uplink), at most two business users are possible in a PON because it would not be possible to guarantee 1 Gb/s to three users during 100% of the time. Thus, the maximum number of premium users $N_p$ is limited to

$$r_b^{(\max)} = \left\lfloor \frac{C_{UL}}{B_{\text{peak}}} \right\rfloor. \tag{9}$$

Next, the goal is to find the largest value of residential users $r_r^{(\max)}$ for sharing the remaining capacity not used by

TABLE II
BANDWIDTH COMPARISON BETWEEN THE FOUR NG-PON TECHNOLOGIES: AVERAGE BANDWIDTH AND PERCENTAGE OF TIME THAT $b = 1$ Gb/s

| | 1:4 | 1:8 | 1:16 | 1:32 | 1:64 |
|---|---|---|---|---|---|
| $E(b)$, $\beta$ | | | $q = 15\%$ | | |
| GPON | 956 Mb/s, 89% | 847 Mb/s, 65% | 612 Mb/s, 28.4% | 323 Mb/s, 3% | 145 Mb/s, ~0% |
| XG-PON | 998 Mb/s, 99% | 978 Mb/s, 89% | 871 Mb/s, 56% | 588 Mb/s, 12% | 289 Mb/s, 0.2% |
| TWDM | 1000 Mb/s, 100% | 1000 Mb/s, 100% | 998 Mb/s, 99% | 978 Mb/s, 89% | 871 Mb/s, 56% |
| WDM-PON | | – | – | 1000 Mb/s, 100% | – |
| $E(b)$, $\beta$ | | | $q = 50\%$ | | |
| GPON | 670 Mb/s, 31% | 363 Mb/s, 4% | 168 Mb/s, ~0% | 80 Mb/s, ~0% | 40 Mb/s, ~0% |
| XG-PON | 935 Mb/s, 69% | 665 Mb/s, 14% | 336 Mb/s, ~0% | 162 Mb/s, ~0% | 79 Mb/s, ~0% |
| TWDM | 1000 Mb/s, 100% | 1000 Mb/s, 100% | 935 Mb/s, 69% | 665 Mb/s, 14% | 336 Mb/s, ~0% |
| WDM-PON | | – | – | 1000 Mb/s, 100% | – |

TABLE III
BANDWIDTH COMPARISON FOR DIFFERENT BUSINESS/RESIDENTIAL CONFIGURATIONS IN GPON, XG-PON, AND TWDM-PON

| | $x_b$ | | |
|---|---|---|---|
| $E(b_r)$, $\beta_r$ | 0 | 1 | 2 |
| GPON 1:1 | 1000 Mb/s, 100% | – | – |
| GPON 1:2 | 991 Mb/s, 98% | 943 Mb/s, 94% | – |
| GPON 1:4 | 956 Mb/s, 89% | 840 Mb/s, 78% | – |
| GPON 1:8 | 847 Mb/s, 66% | 664 Mb/s, 52% | – |
| GPON 1:16 | 612 Mb/s, 28% | 424 Mb/s, 20% | – |
| GPON 1:32 | 323 Mb/s, 4% | 204 Mb/s, 2% | – |
| XG-PON 1:2 | 1000 Mb/s, 100% | 1000 Mb/s, 100% | – |
| XG-PON 1:4 | 997 Mb/s, 99% | 991 Mb/s, 97% | 961 Mb/s, 92% |
| XG-PON 1:8 | 978 Mb/s, 89% | 947 Mb/s, 82% | 871 Mb/s, 72% |
| XG-PON 1:16 | 870 Mb/s, 56% | 795 Mb/s, 46% | 678 Mb/s, 37% |
| XG-PON 1:32 | 589 Mb/s, 12% | 499 Mb/s, 9% | 395 Mb/s, 6% |

business users, while at the same time they are provided 1 Gb/s during a minimum percentage of time $\beta_r$. In other words, it is necessary to compute each combination of business $x_b$ $(0 \leq x_b \leq r_b^{(\max)})$ and residential $x_r$ $(0 \leq x_r \leq r_{\text{tot}} - r_b)$ users in a PON tree and check whether or not the $\beta_r$ is guaranteed for such a number of residential users. Table III shows the values of average bandwidth perceived by the residential users $E(b_r)$ and percentage of time where 1 Gb/s is provided to them $\beta_r$ for every possible combination.

As shown in the table, GPON allows split ratios up to 1:16 with 0 or 1 business user. In the case of $x_b = 0$ business users, those residential users who are active share the 1.25 Gb/s upstream capacity, while in the case of $x_b = 1$ business user, the active residential users share 1.25 Gb/s when the business user is inactive (50% of the time) and only 0.25 Gb/s when the business user is active (the other 50% of the time).

In the case of XG-PON, the topology allows at most two business users. Active residential users share the bandwidth unused by business users, showing split ratios up to 1:16 where $\beta_r$ is guaranteed. It is worth remarking that TWDM-PON comprises a stacking of four XG-PONs; hence, the values of XG-PON 1:$x$ are also the same as the values of TWDM-PON 1:4$x$ (i.e., XG-PON 1:8 shows the same $E(b_r)$ and $\beta_r$ as TWDM-PON 1:32).

## IV. OPTIMIZED NETWORK DEPLOYMENT ON A GEOGRAPHICAL AREA

This subsection develops an optimization framework based on mixed integer linear programming (MILP), which will drive the cost-optimized deployment for the set of technologies under consideration. We take as a starting point the notation and model of [15] with the following differences: (1) PON branches contain residential and business users with different network parameters and variables (ONTs and distribution fibers), and (2) residential and business users have different statistical guarantees for 1 Gb/s, which leads to further constraints on the split ratio and on the distribution of residential/business subscribers on each PON. We shall use the settings obtained from the analysis in the previous section, but the methodology is applicable to other combinations of business and residential subscribers.

### A. Network Parameters and Variables

This subsection details parameters, sets, and variables used in the optimization model.

Let C denote locations where central offices are placed, M denote the set of fiber access points (FAPs) where splitters/AWGs are placed, and O or B denote the set of ONTs where business or residential ONTs, respectively, are placed. COs and FAPs are connected using a single optical fiber, as well as it happens between FAPs and ONTs. The fiber distance between the $c$th CO and the $m$th FAP is named $l_{c,m}$, while the distance between each $m$th FAP and the $o$th or $b$th ONT is named $l_{m,o}$ or $l_{m,b}$. The distance has an impact on the cost; clearly, the longer the distance, the higher the cost. Maximum distance is limited as $l_{\max}$ due to technological considerations. The remaining parameters follow:

- $n_u$: number of residential ONT locations;
- $n_b$: number of business ONT locations;
- $n_v$: number of FAP locations that can host splitters or AWGs;
- $n_w$: number of central offices (COs);
- $n_p$: number of PONs. Each line card can contain a maximum number of PONs, different for each technology;
- $r$: split ratio;
- $r_b$: maximum number of business ONTs in the tree;
- $C$: set of central office locations, where $|C| = n_w$;
- $M$: set of FAP locations, where $|M| = n_w$;
- $O, B$: set of residential or business ONT locations, where $|O| = n_u$ and $|B| = n_b$.

In terms of binary and integer variables, the following are used in the optimization framework. Again, we take the notation of [15] as a basis in order to benefit the reader and make this paper compatible.

Binary variables follow:

- $f_{c,m}$ is set to 1 (or 0) if there is (or not) a fiber connection between the $c$th CO and the $m$th FAP;
- $d_{m,o}$ is set to 1 (or 0) if there is (or not) a fiber connection between the $m$th FAP and the $o$th residential ONT;
- $e_{m,b}$ is set to 1 (or 0) if there is (or not) a fiber connection between the $m$th FAP and the $b$th business ONT;
- $s_m$ is set to 1 if one splitter (as a minimum) is placed at the $m$th FAP; 0 otherwise.

Integer variables follow:

- $\bar{f}_{c,m}$ is the number of fiber connections between the $c$th CO and the $m$th FAP,
- $\bar{s}_m$ is the number of splitters or AWGs located at the $m$th FAP location,

- $\bar{x}_c$ is the number of line cards located at the $c$th CO location.

### B. Cost Components

The total deployment cost of a PON network is based on a number of individual components (Table IV), which are added up: cost of fibers, equipment, splitters/AWG, and labor cost. We assume a brownfield deployment scenario for network design, where operators already have COs, FAPs, and ducts deployed for telephony/ADSL and wish to take advantage of those facilities to deploy FTTH/FTTB equipment and fiber.

In this model, the cost of fiber depends on the type and length of fibers used in the distribution and feeder sections, with $\eta_f$ being the cost per unit of feeder fiber and $\eta_d$ the cost per unit of distribution fiber. For the sake of simplicity, these figures include the cost of deployment of fiber through the ducts in these figures.

The cost of equipment includes ONTs and OLTs. ONT costs are different for residential and business customers and also depend on the PON technology. Let $\eta_o$ be the cost of a residential ONT and $\eta_b$ of a business ONT. Each OLT consists of a chassis, common equipment, and line cards. The cost of the OLT chassis, including common equipment, is denoted as $\eta_{ch}$. Typically, each OLT is connected to the metro network through an Ethernet switch, whose cost per port is denoted as $\eta_e$. The number of line cards on the chassis is dependent on the number of PONs required: $\eta_{olt}$ is the cost of each line card. There is also a cost associated with the fiber distribution panels at the CO, which connects the OLT line cards with the outside plant fiber: this cost is denoted as $\eta_k$.

In terms of splitters/AWG, there is a cost associated with the installation of the first splitter or AWG in a FAP, which includes the installation of the enclosure, and then a different cost every time a new splitter or AWG is added to that FAP. The cost, when the first splitter or AWG is installed is $\eta_s$, while we denote $\eta_a$ as the cost when an additional splitter/AWG is installed. Those cost values depend on the splitting ratio: the higher the split, the higher is the cost.

Labor costs include the cost required to send people to a FAP location or cost associated with the work performed at a CO location. The major portion of labor costs are associated with sending people to the FAP locations in order to install splitters/AWG and make splices, and this is denoted as $\eta_l$ and $\eta_i$, respectively. The cost associated with the activities at the CO location, for example, installation of the OLT, is denoted as $\eta_{lc}$. All these costs are summarized in Table IV.

TABLE IV
PARAMETERS FOR COST COMPONENTS

| Costs | Notation | Description |
|---|---|---|
| Fiber | $\eta_d$ | Cost of distribution fiber (unit length) |
| | $\eta_f$ | Cost of feeder fiber (unit length) |
| Equipment | $\eta_o$ | Cost of residential ONT |
| | $\eta_b$ | Cost of business ONT |
| | $\eta_{ch}$ | Cost of OLT chassis and common equipment |
| | $\eta_{olt}$ | Cost of OLT line card |
| | $\eta_e$ | Cost of Ethernet port to connect to metro network |
| | $\eta_k$ | Cost of fiber distribution panel at CO |
| Splitter/ AWG | $\eta_s$ | Cost of first splitter/AWG at the FAP |
| | $\eta_a$ | Cost of an additional splitter/AWG |
| Labor | $\eta_l$ | Cost of installing splitter/AWG |
| | $\eta_i$ | Cost per splice |
| | $\eta_{lc}$ | Cost of installation at CO |

### C. Objective Function and Constraints

The objective is to find the technology with minimum total deployment cost [16], which guarantees the respective statistical service levels planned for residential and business customers by means of oversubscription, as described in the previous sections. To this end, we define the following objective function for the optimization problem as follows:

$$\begin{aligned}\min\ & \eta_f \sum_{c\in C}\sum_{m\in M} l^f_{c,m}\bar{f}_{c,m} \\ & + \eta_d \sum_{m\in M}\sum_{o\in O} l^d_{m,o} d_{m,o} + \eta_d \sum_{m\in M}\sum_{b\in B} l^d_{m,b} e_{m,b} \\ & + \sum_{c\in C}\bar{x}_c \eta_{olt} + n_w(\eta_{ch} + \eta_e) \\ & + \sum_{m\in M}\bar{s}_m\eta_k + \sum_{m\in M} s_m\eta_s + \sum_{m\in M}(\bar{s}_m - s_m)\eta_a \\ & + n_u\eta_o + n_e\eta_b + n_w\eta_{lc} \\ & + \sum_{m\in M} s_m\eta_l + \left(n_u + n_e + \sum_{m\in M}\bar{s}_m\right)\eta_i. \end{aligned} \tag{10}$$

Description of the different terms involved in Eq. (10) can be found in Table V. The optimization problem must also include some constraints in order to ensure that the resulting network design satisfies realistic network requirements, such as ensuring that each splitter is connected to only one ONT, or that fiber length does not exceed the maximum PON transmission distance. Those constraints are the following:

*1) Constraint on the Feeder Fiber Connectivity:* Each splitter must be connected to only one PON port. Each feeder fiber connection from the CO is only established with FAPs containing at least one splitter/AWG installed:

$$\sum_{c\in C}\bar{f}_{c,m} = \bar{s}_m, \quad \forall m \in M. \tag{11}$$

*2) Constraints on the Distribution Fiber Connectivity:* Equations (12) and (13) reflect that business and residential ONTs are always connected to only one FAP. Equations (14) and (15) ensure that when there is a residential or business ONT connected to a FAP, that FAP contains at least one splitter or AWG:

TABLE V
Terms for Optimization Model

| Terms | Description | Subsection V.C |
|---|---|---|
| $\eta_f \sum_{c\in C} \sum_{m\in M} l^f_{c,m} \bar{f}_{c,m}$ | Total cost of feeder fiber | Feeder fiber |
| $\sum_{m\in M} \sum_{o\in O} l^d_{m,o} d_{m,o} + \eta_d \sum_{m\in M} \sum_{b\in B} l^d_{m,b} e_{m,b}$ | Total cost of distribution fiber, residential, and business | Distribution fiber |
| $\sum_{m\in M} \bar{s}_m \eta_k$ | Total cost of feeder fiber connectivity at CO | Passive |
| $\sum_{m\in M} s_m \eta_s$ | Cost of first splitter | Passive |
| $\sum_{m\in M} (\bar{s}_m - s_m)\eta_a$ | Cost for additional splitter | Passive |
| $\sum_{m\in M} s_m \eta_l$ | Installation cost of splitters at selected FAPs | Passive |
| $(n_u + n_e + \sum_{m\in M} \bar{s}_m)\eta_i$ | Total residential and business splicing cost | Passive |
| $n_u \eta_o$ | Total cost of residential ONTs | Residential ONT |
| $n_e \eta_b$ | Total cost of business ONTs | Business ONT |
| $\sum_{c\in C} \bar{x}_c \eta_{olt}$ | Total cost of OLT line cards | Common active |
| $n_w(\eta_{ch} + \eta_e)$ | Total cost of OLT chassis | Common active |
| $n_w \eta_{lc}$ | Labor cost at CO | Common active |

$$\sum_{m\in M} d_{m,o} = 1, \quad \forall o \in O, \tag{12}$$

$$\sum_{m\in M} e_{m,b} = 1, \quad \forall b \in B, \tag{13}$$

$$d_{m,o} \le s_m, \quad \forall m \in M, \quad \forall o \in O, \tag{14}$$

$$e_{m,b} \le s_m, \quad \forall m \in M, \quad \forall b \in B. \tag{15}$$

*3) Nonlinear Relationship Between $f_{c,m}$ and $\bar{f}_{c,m}$:* $f_{c,m}$ is a binary variable that indicates a connection between the $c$th CO and the $m$th FAP, while $\bar{f}_{c,m}$ is an integer with the number of fiber connections. The relationship between them is $f_{c,m} = \min\{1, \bar{f}_{c,m}\}$. Equation (16) sets the binary $f_{c,m}$ to zero if $\bar{f}_{c,m}$ is zero, and Eq. (17) sets the binary $f_{c,m}$ to one when the corresponding integer is nonzero:

$$\bar{f}_{c,m} \ge f_{c,m}, \quad \forall c \in C, \quad \forall m \in M, \tag{16}$$

$$\bar{f}_{c,m}/(n_u + n_b) \le f_{c,m}, \quad \forall c \in C, \quad \forall m \in M. \tag{17}$$

*4) Constraints on the Split Ratio and Business Subscribers in the PON:* This constraint affects the amount of ONTs that can be connected in a PON tree. For example, an XG-PON tree with a 1:16 split can support up to a maximum of 16 ONTs. Equation (18) indicates the number of maximum residential and business ONTs per tree, while Eq. (19) shows, on a per tree basis, the maximum number of business ONTs ($r_b$) because they are the most restrictive in terms of bandwidth consumption:

$$\sum_{o\in O} d_{m,o} + \sum_{b\in B} e_{m,b} \le r\bar{s}_m, \quad \forall m \in M, \tag{18}$$

$$\sum_{b\in B} e_{m,b} \le r_b \bar{s}_m, \quad \forall m \in M. \tag{19}$$

*5) Constraints on the Span of the PON:* The power budget of the span of the PON, which depends on the split ratio, determines the maximum distance, $l_{\max}$, between the CO and the ONT. For example, a typical GPON budget with a 1:32 splitter corresponds to around 20 km. Because residential and business ONTs can be connected through different split ratios, there are two equations, Eqs. (20) and (21), to cover this constraint for residential and business ONTs:

$$l^f_{c,m} f_{c,m} + l^d_{m,o} d_{m,o} \le l_{\max}, \\ \forall c \in C, \quad \forall m \in M, \quad \forall o \in O, \tag{20}$$

$$l^f_{c,m} f_{c,m} + l^d_{m,b} e_{m,b} \le l_{\max}, \\ \forall c \in C, \quad \forall m \in M, \quad \forall b \in B. \tag{21}$$

*6) Nonlinear Relationship Between $s_m$ and $\bar{s}_m$:* Similar to Eqs. (16) and (17), it is required to set the relationships between $s_m$ (binary variable set to one or zero if there is one or no splitter, respectively, at the $m$th FAP location) and $\bar{s}_m$ (integer variable that indicates the number of splitters at the $m$th FAP location). The relationship between them is the following: $s_m = \min\{1, \bar{s}_m\}$, which is represented by the following restrictions:

$$\bar{s}_m \ge s_m, \quad \forall m \in M, \tag{22}$$

$$\bar{s}_m/(n_u + n_b) \le s_m, \quad \forall m \in M. \tag{23}$$

*7) Constraints on the Number of PONs per Line Card:* Number of residential and business PON trees, $\bar{f}_{c,m}$ and $\bar{g}_{c,m}$, respectively, requires a number of line cards for the $c$th CO location. This relationship is represented by the following: $\bar{x}_c = [(\sum_{m\in M}(\bar{f}_{c,m} + \bar{g}_{c,m})/n_p)]$. This nonlinear relationship is represented by the following constraints:

$$\bar{x}_c \ge \left(\sum_{m\in M} \bar{f}_{c,m}\right)/n_p, \quad \forall c \in C, \tag{24}$$

$$\bar{x}_c < \left(\sum_{m\in M} \bar{f}_{c,m}/n_p\right) + 1, \quad \forall c \in C. \tag{25}$$

*8) Bounds on Decision Variables:* Mandatory bounds for binary and integer variables for the MILP simulation:

$$\bar{s}_m \geq 0, \quad \forall m \in M,$$

$$\bar{f}_{c,m} \geq 0, \quad \forall c \in C, \quad \forall m \in M,$$

$$\bar{x}_c \geq 0, \quad \forall c \in C,$$

$$f_{c,m} \in \{0,1\}, \quad \forall c \in C, \quad \forall m \in M,$$

$$d_{m,o} \in \{0,1\}, \quad \forall m \in M, \quad \forall o \in O,$$

$$e_{m,b} \in \{0,1\}, \quad \forall m \in M, \quad \forall b \in B,$$

$$s_m \in \{0,1\}, \quad \forall m \in M.$$

## V. Model Evaluation

### A. Data Set

The network topology used for evaluation comprises a real deployment in Rio de Janeiro (Brazil). Network parameters are discussed in Subsection IV.A. The network comprises one central office location ($n_w$, represented by a blue star in the figure), five FAP locations ($n_v$, represented by red squares) and 75 ONTs, some of which are residential ($n_u$), and the rest are business ($n_b$) subscribers. FAPs may contain one or more residential/business splitters or AWGs. The placement of the different components is chosen according to the network planning of a major undisclosed service provider.

The maximum distance ($l_{\max}$) between the CO and an ONT is set to 20 km, while the split ratio ($r$) and number of PONs per line card ($n_p$) are dependent on the technology under evaluation. For example, the number of PONs per line card for GPON is 16, while this number for XG-PON and TWDM-PON is 4, and the same number for WDM-PON is 1.

All technologies under consideration are deployed with a single fiber between the CO and the FAP, and a single fiber between the remote node (splitter or AWG) and the ONT. Thus, the main difference in terms of price does not correspond to fiber but to the central office, remote node, and ONT prices. The other costs, such as fiber, labor, or equipment costs, are described in Subsection IV.B and are also inputs for the optimization model. Market prices of either available commercial equipment (GPON, XG-PON, and WDM-PON) or prototypes (TWDM-PON) have been extracted from different sources [17,18].

Only those FTTH technologies capable of achieving the required service levels for residential and business subscribers have been considered. It is worth remarking that, in our target scenario, residential subscribers demand 1 Gb/s during a minimum of $\beta_r = 20\%$ of the time ($q_r = 15\%$ assumed), while business users require $\beta_b = 100\%$ and $q_b = 50\%$. Therefore, only some split ratios, according to the capacity planning requirements, are selected. For example, GPON 1:8 is selected because it can provide 1 Gb/s to residential users during at least 65% of the time (greater than $\beta_r = 20\%$), but XG-PON 1:32 will not be considered because it does not meet the $\beta$ requirement (Table II). In this light, the following split configurations have been analyzed: GPON between 1:1 and 1:8, XG-PON between 1:2 and 1:16, TWDM-PON between 1:8 and 1:64, and WDM-PON 1:32. Oversubscription factors beyond the feeder fiber (i.e., from the OLT towards the metro) are not considered.

### B. Optimal Solution

We have used the *lpSolve* library [19] and MILP to solve our optimization model. Although MILP computation can take substantially longer than heuristic algorithms, it provides exact solutions to the optimization problem and takes acceptable times if the network size is small, as it is in our Rio de Janeiro case (1 CO, 5 FAPs, and 75 ONTs). However, it is necessary to point out that a cost-optimal solution with thousands of ONTs will likely require a heuristic approach or partitioning the problem into geographical areas.

In all data sets under consideration, we have used a single CO covering the FTTH deployment in Rio de Janeiro (Brazil). All data sets consist of the same network topology in terms of number and location of FAPs and ONTs. Fiber routes follow the existing streets in the city.

For each data set, we consider one of the four PON technologies and apply the right constraints, selecting the right split ratio ($r$) that supports 1 Gb/s during 20% of the time for residential users and 100% for business users, and also maximum number of business users per tree ($r_b$). The remaining parameters, namely, fiber costs, labor costs, or fixed costs associated with equipment are selected for each technology as appropriate.

After execution of the optimization algorithm, results include the total cost associated with the cost-optimal network deployment; FAP locations where the splitters or AWG can be installed; number of line cards at the CO location (in our case, there is a single CO); as well as connectivity between the CO and FAPs and between FAPs and ONTs.

Figure 3 shows a map with the optimization results and connectivity topology between the CO and the FAPs for the TWDM-PON 1:64 scenario under the assumption of 67 residential ONTs and eight business ONTs (i.e., approximately 10% business users), which resulted in the cheapest technological solution for this percentage of business users (Fig. 6). Fiber route distances have been calculated using *Google Maps API* and the distance matrix service, which returns street routes. For simplicity and clarity, only logical connectivity (not street routes) between FAPs and some ONTs is shown.

### C. Economic Analysis

In this subsection, we analyze the capital expenditure (CAPEX) for all technologies as well as the contribution of the different components to the cost-optimized model. Figure 4 shows the total deployment cost relative to the

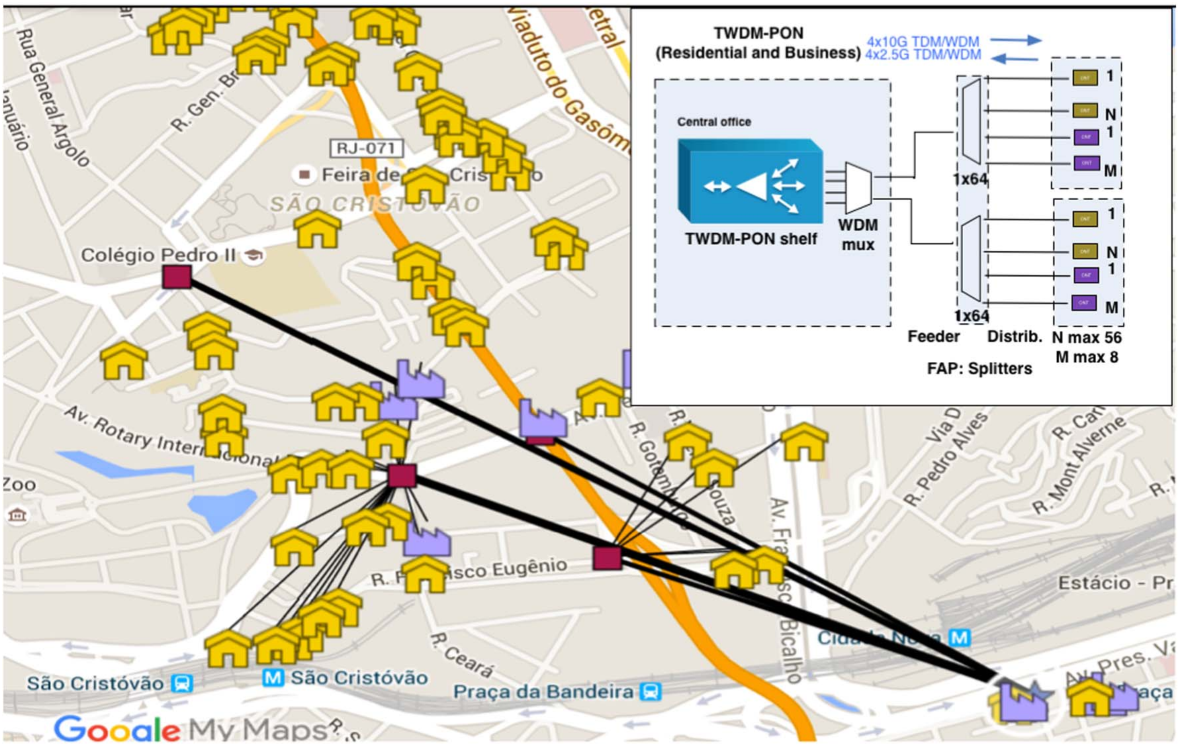


Fig. 3. Cost-optimal solution for TWDM-PON 1:64 (67 residential and eight business ONTs).

most expensive technology, according to the percentage of business users among the total (from 0% to 100%). Figure 5 removes the ODN-related costs in order to show only the active and passive elements.

Figures 6 and 7 show the particular cases when 10% (left figures) and 60% (right figures) of subscribers are business. The case with ∼10% business subscribers considers eight business and 67 residential ONTs in the scenario, while the ∼60% business-users case represents 46 business and 29 residential ONTs. Cost components, as described in Table V, include the following:

- **Feeder fiber**: cost of fiber and fiber deployment (digging and preparing the trench, manholes, etc. is included in this scenario). As per Fig. 1, for GPON, XG-PON, and TWDM-PON, the feeder fiber is the fiber between the central office and the power splitter, while for WDM-PON, the feeder represents the fiber between the central office and the AWG.
- **Distribution fiber**: same as before but applied to the distribution fiber. As per Fig. 1, distribution fiber is the fiber between the power splitter (GPON, XG-PON, TWDM-PON) or AWG (WDM-PON) and the residential or the business ONT.
- **Active and Passive**: passive components, ONTs, and common active equipment are shown in Fig. 7 as follows:
  - **Passive:** cost of the cabinet, splitters, or AWGs where appropriate, patch cables, and cost of splicing the fibers. For GPON, splits between 1:1 and 1:8 are considered, for XG-PON between 1:2 and 1:16, and for TWDM-PON between 1:8 and 1:64. In the case of WDM-PON, a 1:32 AWG is assumed.
  - **Residential ONT:** lowest cost of commercially available units equipped with at least 4 GB Ethernet ports toward the user.
  - **Business ONT:** lowest cost of commercially available units equipped with at least 4 GB Ethernet ports toward the business user. Business ONTs are typically more expensive because they can provide advanced OAM functionalities, among others.
  - **Common active:** cost of core cards of the OLT shelves, including line cards shared across residential and business subscribers, one-time software licenses, and everything necessary for in-service operation. OLT line cards are equipped with 16 ports for GPON, four ports for XG-PON/TWDM-PON, and one port for WDM-PON.

As expected, the largest part of the CAPEX is due to the physical infrastructure [20] (feeder and distribution fiber). In our case, it represents more than 90% of the total investment for two reasons: first, fiber distances are long (an average of 2 km for feeder, and 1.5 km for distribution); second, the scenario contains a relatively small numbers of ONTs, i.e., the scenario is not fulfilled with all potential subscribers supported by an OLT shelf (only 75 ONTs are considered); therefore, the percentage of physical infrastructure cost over the total value is expected to decrease as the number of users grow.

Figure 4 shows that TWDM-PON is the cheapest technology in our case for a low number of business subscribers,

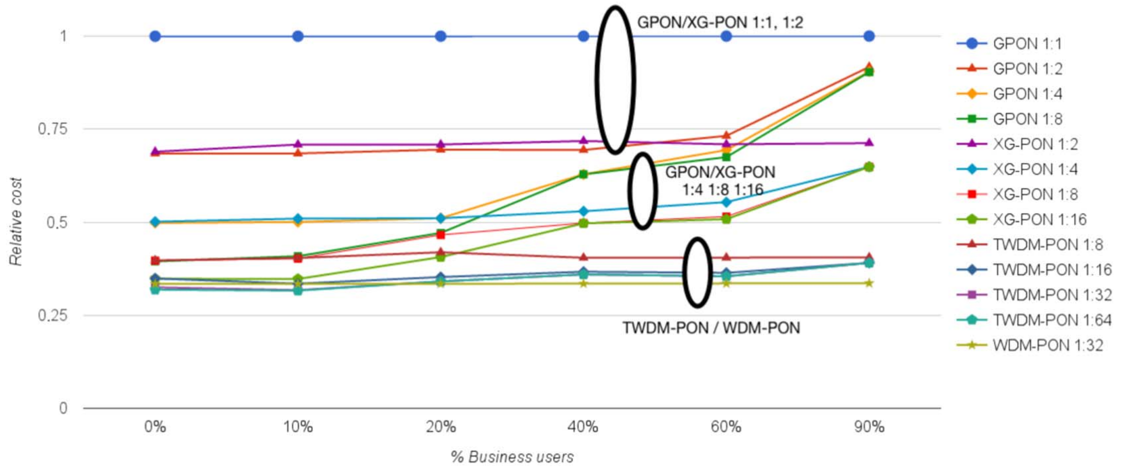


Fig. 4. Normalized total optimal cost. All technologies.

but, as the percentage of business increases (≥ ~20%), then WDM-PON results in the cheapest one. GPON and XG-PON with high split ratios (1:4, 1:8, and 1:16) show a significant cost increase as the percentage of business users grow. It must be noted that the average percentage of business users in a whole city is usually small. However, as in our target sample deployment scenario, the network planning may cover just a district of a city that includes a large business area. Finally, GPON (1:1 and 1:2) and XG-PON 1:2 show the highest cost because they are almost point-to-point and, therefore, are penalized by fiber cost.

Excluding the physical infrastructure, i.e., only considering active and passive components, then GPON and TWDM-PON are the winners, as shown in Fig. 5. Theoretically, across all TDM-PON technologies, GPON has the lowest cost per user, then XG-PON, then TWDM-PON. However, TWDM-PON gets benefits in this scenario due to higher split ratios supported with respect to XG-PON (1:32 and 1:64), which positions it at the same cost level as GPON. Figure 5 also reveals that some technologies exhibit flat costs with respect to the number of business users; these correspond to the point-to-point technologies such as WDM-PON and GPON 1:1.

Other observations include the following:

- Excluding the physical infrastructure, GPON 1:8 is the cheapest technology and is capable of providing 1 Gb/s during a major portion of time. However, GPON does not scale up (see Table II) and is not compliant for splits larger than eight, which makes GPON expensive when total cost is compared. Other technologies, such as TWDM-PON and WDM-PON, are more scalable for providing 1 Gb/s to users.
- As expected, for a similar technology (GPON, XG-PON, TWDM-PON), the cost decreases as the split ratio increases.
- ONTs are cheaper in GPON, due to electronics managing less bandwidth; XG-PON ONTs comes next, followed by TWDM-PON and WDM-PON.
- The cost of XG-PON is more expensive than TWDM-PON, although both provide similar performance levels. This is a consequence of the fact that TWDM-PON stacks four XG-PONs.
- WDM-PON (Fig. 7) is expected to have higher electronics costs at the OLT because one laser per user is required and shelf density is lower (typically 256 users per shelf).

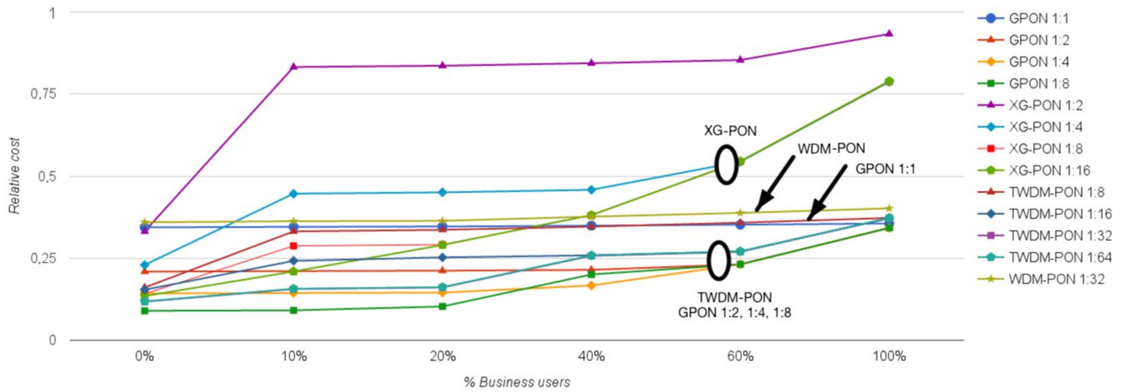


Fig. 5. Details for active and passive components. All technologies.

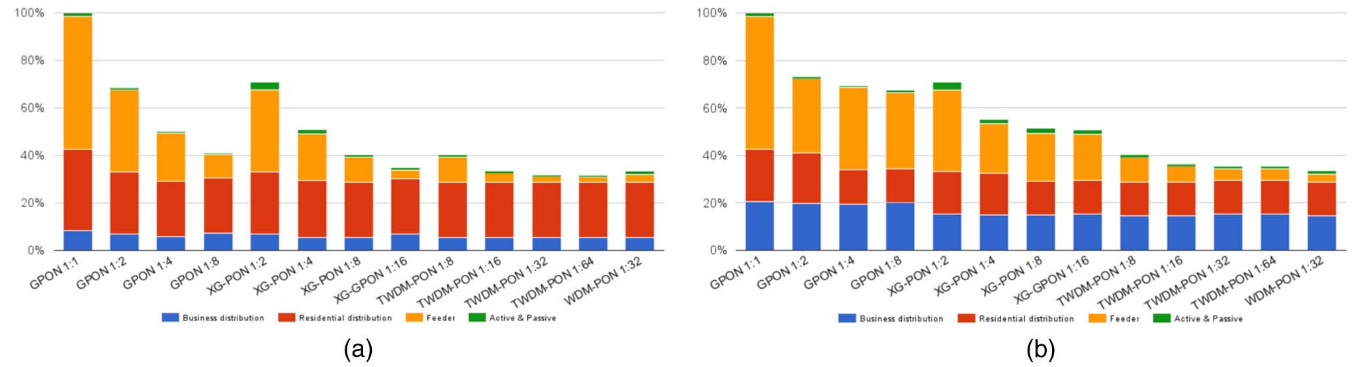


Fig. 6. Normalized total optimal cost for the deployment of (a) eight business and 67 residential ONTs (~10%) and (b) 46 business and 29 residential ONTs (~60%).

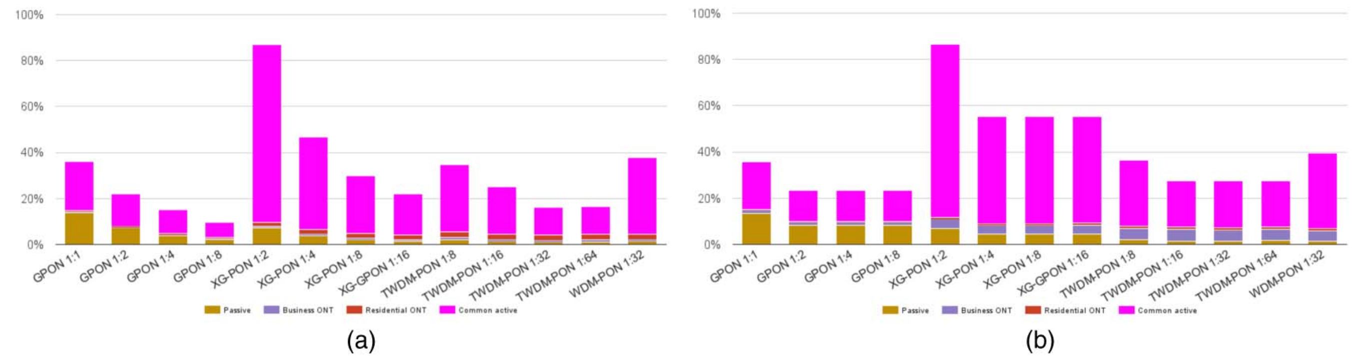


Fig. 7. Details for active and passive components for (a) eight business and 67 residential ONTs (~10%) and (b) 46 business and 29 residential ONTs (~60%).

However, WDM-PON results in being more affordable due to a higher split ratio than other technologies (AWG 1:32) and low number of ONTs in the scenario (75 users).

### *D. Suitability of WDM-PON Against TWDM-PON for Business Services*

TWDM-PON is a cheaper solution than WDM-PON for some scenarios and can provide 1 Gb/s nearly 100% of the time for residential and business subscribers. However, it gets penalized in cost when the number of business subscribers grows because the upload of 2.5 Gb/s restricts the number of business subscribers supported per PON tree to two at most, as previously explained.

On the contrary, WDM-PON provides 1 Gb/s guaranteed 100% of the time regardless of the number of subscribers in the PON tree and results in being the best option as the number of business subscribers grows. Additionally, other advantages of WDM-PON are that it can provide long reach (given the low insertion loss of AWG), advanced troubleshooting capabilities [21], the possibility to individually adapt bitrates on a per-wavelength basis, and especially security, a remarkable feature for a business customer because users do not receive other user's traffic.

## VI. Summary and Conclusions

This article has analyzed the potential of next-generation PONs in providing 1 Gb/s symmetrical services in a dual residential-business exploitation scenario. In particular, GPON, XG-PON, WDM-PON, and the emerging TWDM-PON technologies with different split ratios have been studied. Only those split ratios guaranteeing service-level agreements are considered, including split ratios up to 1:8 for GPON, 1:16 for XG-PON, 1:64 for TWDM-PON, and 1:32 for WDM-PON, yielding a total of 15 different deployments, each of them with different percentages of business subscribers between 0% and 100%. An MILP-based optimization model has been proposed to obtain the best topology configuration in the 15 cases for a realistic deployment scenario in Rio de Janeiro.

The results of this simulation show that TWDM-PON is the most affordable solution when the rate of business subscribers is low, but, as this percentage increases over the total subscribers, WDM-PON is the winner. Cheaper technologies such as GPON or XG-PON turn out to be more expensive due to the symmetric rate requirement and the 100% of time bandwidth availability required for business subscribers.

Future work will consider the optimization analysis for other geotypes, mainly rural areas, a different combination of number of subscribers, and also additional and more demanding service level agreements such as wireless backhauling.


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